

Control Components Using Si, GaAs, and GaN Technologies

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Control Components Using Si, GaAs, and GaN Technologies

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Preface

Control components are important parts of RF and microwave systems. Their compact size, high performance, and low cost have played a vital role in the development of high-performance, cost-effective solutions and new applications during the past quarter century. PIN diodes, GaAs MESFET, HBT, and HEMT, GaN HEMT, SiGe HBT and Si CMOS technologies have been used to develop a large variety of control components for commercial and military applications. Numerous articles scattered in a wide array of technical journals and conference proceedings, along with book chapters, have been published on control components. However, no comprehensive text dedicated to this topic covering both theory and practical aspects, and recent devices exists. This book not only provides a comprehensive treatment but also deals with HEMT- and CMOS-based control components to fill the void.

Control components constitute switches, phase shifters, attenuators, and limiters. Switches are used for changing the signal flow in different directions, phase shifters manipulates the phase of the transmitted signal, attenuators adjust the amplitude of the signal, while the limiters set the strength of the receive signal at the output of a circuit. A single active phased array radar system, for example, may use thousands of these circuits for precise control of the radiated beam. All these circuit functions are integrated parts of solid-state transmit-receive (T/R) modules.

Traditionally, two types of solid-state devices commonly used in control components are: Si PIN diodes and GaAs MESFETs/HEMTs. Recently, MEMS, CMOS, and GaN HEMTs have been used for RF switches and offer challenges to PIN diodes and MESFETs/HEMTs. Si CMOS-based control components have significantly small die size in comparison to PIN diode and MESFET/HEMT circuits. Applications of MEMS in RF circuits have been discussed in numerous references including some books. This book describes control circuits using solid-state devices. However, many of the circuit configurations and design approaches described in the book are applicable for MEMS technology also.

The GaN HEMT is an emerging solid-state device that exhibits great potential for high-power and high-voltage control components. The operation of GaN HEMTs at high voltages, high currents, and high temperatures offers a promise for a superior performance for RF functions including high-power control components and low-cost transceivers.

The unique characteristics of PIN diodes, MESFETs/HEMTs, CMOS, GaN HEMTs, and other devices are exploited in this book for the design of RF, microwave, and millimeter-wave control components. Control components using GaN HEMT, SiGe HBT, and Si CMOS technologies have made tremendous progress in recent years. These technologies are treated for the first time in a book. Where ever

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possible, the salient features of various technologies are compared qualitatively and quantitatively.

This book evolved basically with the author's extensive control components design experience over the past 40 years. He has been actively involved with switch device development and numerous designs for switches, phase shifters, attenuators, and limiters from the concept level to the end products. The present book provides a comprehensive treatment of such circuits. The contents of the book are selfcontained and cover practical aspects in detail. Device operation and their models, basic circuit theory and designs, and applications are described. Design methods and circuit design examples using both hybrid and monolithic integrated circuits are presented. The topics discussed include modeling, analysis, design, and fabrication considerations. The book also includes extensive design information in the form of equations, tables, graphs, and examples. More than 20 practical examples are fully solved, make it simple to understand the concepts of circuit design. Simple design equations are also included to understand design concepts. The unique features of this book include in-depth study and broad view of solid-state control components. It has dedicated sections on broadband techniques. With its emphasis on theory, design, and practical aspects geared toward day-to-day applications, this book is intended for students, teachers, scientists, and practicing engineers. The students are required to have prior knowledge of topics such as solid-state device basics, theory of transmission lines, basic circuit theory, and electromagnetics taught at the undergraduate level. It is hoped that the readers of this book will further understand RF and microwave control components design.

The book is divided into six chapters, with the material treated precisely and thoroughly covering various aspects of control components in each chapter. The text presents the operation of switching devices and their models, circuit analysis techniques and design, and circuit performance. These chapters provide the foundation for analysis and design of RF, microwave, and millimeter wave control components. It is hoped that the selection of topics and their presentation will meet the expectations of the readers. Like any other comprehensive book, the work of other researchers is included or cited for further reading. This book also includes a comprehensive list of references.

The book contains enough material for a one-year course at the senior or graduate level. With judicious selection of specific topics, one can use the book for one-semester, two-semester, or two-quarter courses.

This book is dedicated to all my colleagues who have done pioneer work in the advancement of microwave engineering. I gratefully acknowledge the association I had with Dr. Edward L. Griffin during my working at ITT and Tyco Electronics. I particularly want to thank George Studtmann for providing several control component examples based on MSAG process. Professor Gabriel Rebeiz and his group on CMOS control components, Professor Robert Caverly on distortion analysis of control devices, and many other researchers who advanced the state of the art in control components are gratefully acknowledged. I would like to acknowledge and sincerely thank Drs. Gabriel Rebeiz, Prasad Shastry, Ernesto Limiti, Andrei Grebennikov, Reza Tayrani, J.-G. Kim, Koen Mouthaan, and Y. P. Zhang for providing and allowing me to use several photographs. This book became a reality only because of the great support I received from Mark Walsh and his staff at Artech House.

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CHAPTER 1

Introduction

Control components constitute switches, phase shifters, attenuators, and limiters. They are employed for controlling the signal flow in transmitters and receivers. Switches are used for changing the signal flow in different directions, phase shifters manipulate the phase of the transmitted signal, attenuators adjust the amplitude of the signal, while the limiters set the strength of the receive signal at the output of a circuit. Control components have been used extensively in radars, communication systems, electronic warfare, wireless applications, cable television (CATV), test instruments, and other systems. All control components are integral parts of solid-state transmit-receive (T/R) modules. A single active phased array radar system, for example, may use thousands of T/R modules for a precise control of the radiated beam. One of the highest volume applications of control components is for switches in mobile or cell and cordless phones, and tens of millions of switches have been used in wireless applications. In this chapter, an overview of control devices and components as well as their applications are provided [1–50].

1.1 History of Control Components

The early history of control components is based on solid-state PIN diodes and ferrites. Using a germanium point contact mixer diode as a switch was reported in 1955. The use of Si-based PIN diodes in switches was proposed in 1958. The work on PIN (or p-i-n, or simply pin) diode limiters and phase shifters started in late 1950s and early 1960s. The ferrite-based control components were reported in 1960s. Ferrite circuits can handle much higher power levels than solid-state devices; however, they are bulkier, are nonreciprocal, and have lower switching speed [1, 2].

Solid-state control components are well documented in early books written primarily on silicon (Si) PIN diode control components [3–9]. Tremendous progress was made based on metal semiconductor field effect transistor (MESFET) or simply FET switching devices to develop low-cost gallium arsenide (GaAs) monolithic microwave integrated circuit (MMIC) switches, phase shifters, and attenuators working up to 40 GHz during the 1980s [10–20]. Multipurpose switches using MESFETs and high electron mobility transistors (HEMTs) led the MMIC technology in 1990s. Control components were also developed using GaAs heterojunction bipolar transistors (HBTs) [49] and silicon germanium (SiGe) HBT [50] –based PIN diodes for low-loss applications. Work on silicon complementary metal oxide semiconductor (CMOS) control components started only in late 1990s. Since then, amazing growth in CMOS radio frequency integrated circuit (RFIC) control components has been

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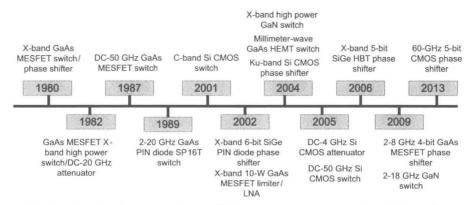


Figure 1.1 Timeline developments of monolithic control components from 1980 to the present.

recorded due to their vast potential in military and commercial applications. The development milestones in MMIC/RFIC control components [25–42] are illustrated in Figure 1.1. More extensive lists of references reporting the past and current progress on control components are included in the succeeding chapters.

During the past two decades, microelectromechanical system (MEMS) devices have been developed for RF switches and variable capacitors. MEMS devices have low loss and are challenging to PIN diodes and transistor control components if long-term reliability issues can be solved. However, MEMS are not as versatile as the solid-state devices when integration with other circuit functions is required. Because it is beyond the scope of this book to discuss MEMS-based control components, readers are referred to numerous published papers/books on this subject [43, 44]. However, many of circuit configurations and design approaches described in this book are applicable for MEMS circuits also.

Since the focus of this book is limited to solid-state control components, no further discussions on ferrite, MEMS, ferroelectric [47, 48] or any other technology used for control components will be included in the book.

1.2 Types of Control Components

Basic types of control components are shown in Figure 1.2. Figure 1.2(a) shows a typical configuration of a three-port switch also known as a single-pole double-throw (SPDT) switch. In this configuration the switching devices are represented as short and open and biased so that they remain ON or OFF under the desired input signal power level. A switch may be a two-port, three-port, or four-port circuit. A popular topology for a phase shifter is shown in Figure 1.2(b). Here phase shifter is realized using two SPDT switches to switch one network to another network having the desired phase difference. Basic configuration of an attenuator is shown in Figure 1.2(c) and has the same concept as the phase shifter (i.e., switching a reference through line to the desired attenuation path). Figure 1.2(d) shows a limiter schematic. Here under ideal conditions, the limiting devices (unbiased or biased) remain open (minimum attenuation) at low signal power levels and are shorted (maximum reflection) at the desired threshold signal power level and beyond. Limiters are designed standalone or they are integrated with low noise amplifiers (LNAs).